Committed Warming and Long-Term Response

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June 6, 2016 – The Ronald J. Stouffer Symposium

Pioneering efforts to study long-term effects of climate change

Century-scale effects of increased atmospheric CO_2 on the ocean–atmosphere system

Syukuro Manabe & Ronald J. Stouffer

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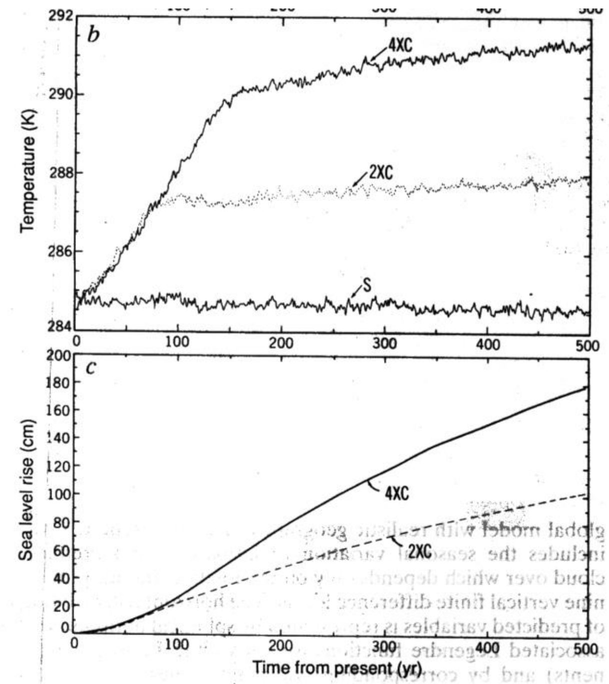
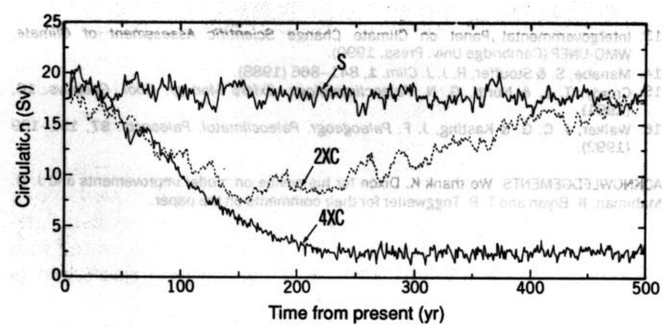
SEVERAL studies have addressed the likely effects of CO_2-induced climate change over the coming decades [1–10], but the longer-term effects have received less attention. Yet these effects could be very significant, as persistent increases in global mean temperatures may ultimately influence the large-scale processes in the coupled ocean–atmosphere system that are thought to play a central part in determining global climate. The thermohaline circulation is one such process — Broecker has argued[11] that it may have undergone abrupt changes in response to rising temperatures and ice-sheet melting at the end of the last glacial period. Here we use a coupled ocean–atmosphere climate model to study the evolution of the world's climate over the next few centuries, driven by doubling and quadrupling of the concentration of atmospheric CO_2. We find that the global mean surface air temperature increases by about 3.5 and 7 °C, respectively, over 500 years, and that sea-level rise owing to thermal expansion alone is about 1 and 2 m respectively (ice-sheet melting could make these values much larger). The thermal and dynamical structure of the oceans changes markedly in the quadrupled-CO_2 climate — in particular, the ocean settles into a new stable state in which the thermohaline circulation has ceased entirely and the thermocline deepens substantially. These changes prevent the ventilation of the deep ocean and could have a profound impact on the carbon cycle and biogeochemistry of the coupled system.

NATURE · VOL 364 · 15 JULY 1993



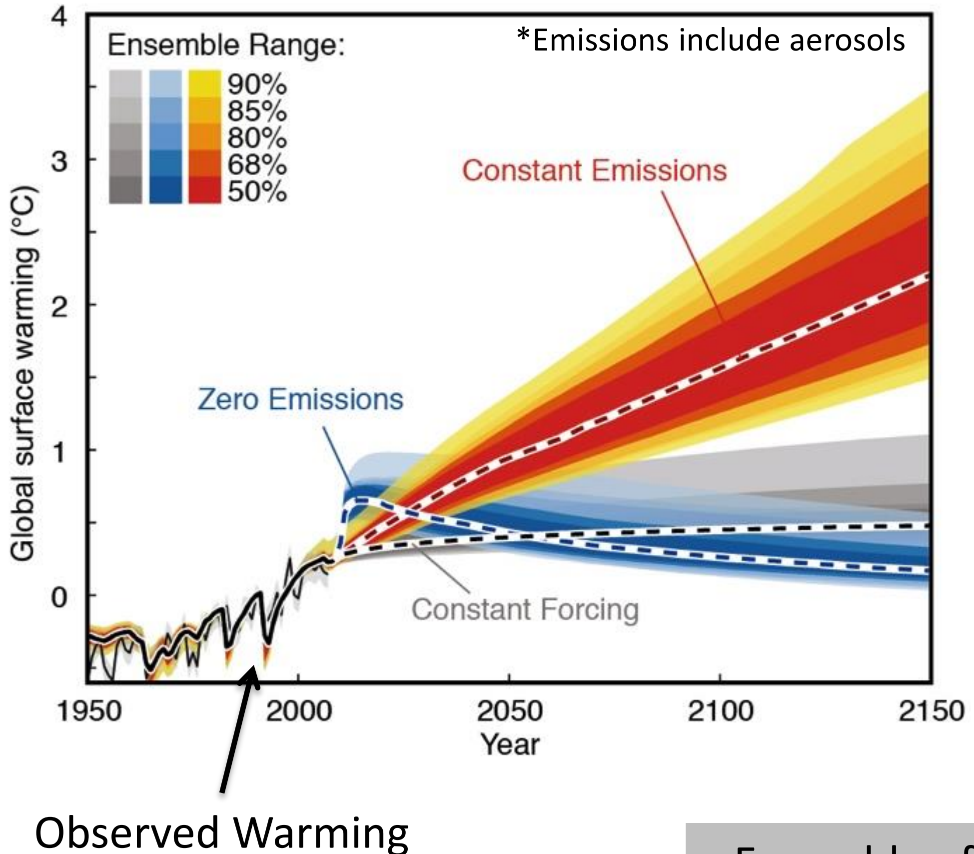


Committed Warming

- Climate change can be thought of as:
  - Warming -- resulting from **current** and **future** anthropogenic activity
  - Warming -- already “**committed**” to based on **past** anthropogenic activity

Anthropogenic activity is taken as the sum of well-mixed greenhouse gas emissions, aerosol emissions, land use, and land cover changes.

Types of commitment



- **Constant-emissions**, CO_2 concentrations continue to rise
- **Zero-emissions**, letting the Earth system attempt to re-equilibrate
- **Constant-forcing**, where atmos. CO_2 concentrations are remain steady

Ensemble of MAGICC simulations based on CMIP3 and C4MIP models (From IPCC AR5 WGI and Hare and Meinshausen 2006)

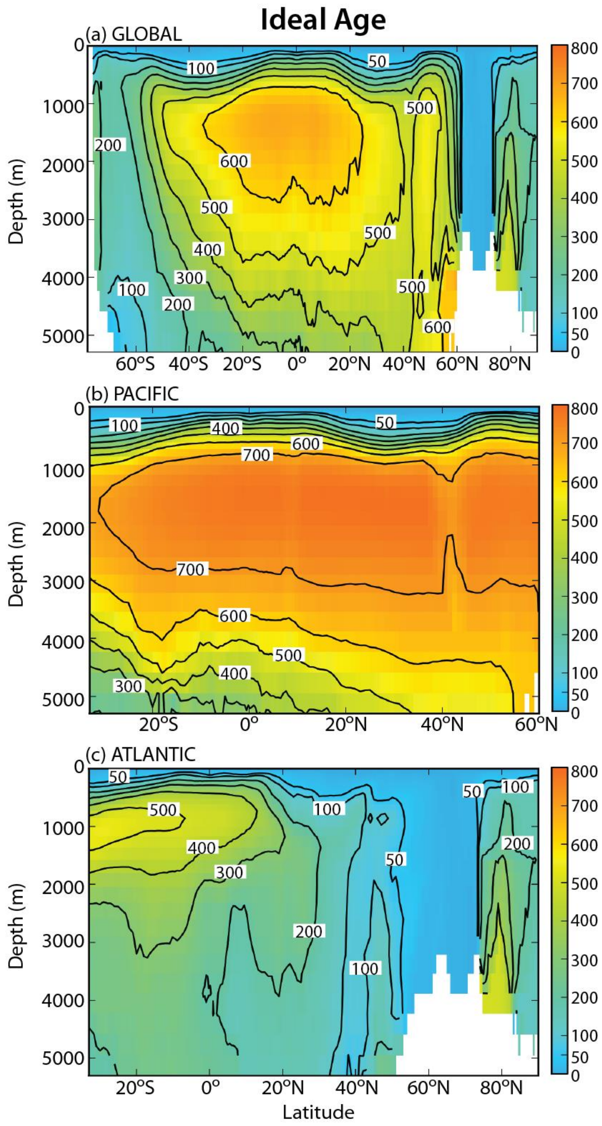
Committed warming controlled by ocean time scales

- Committed warming is a reflection of the deep, less-ventilated ocean experiencing the climate change signal, brought about by:

  - Dynamical changes
    (THC, wind-driven gyres)

  - Direct warming

Ideal age distributions from GFDL-ESM2G
Pre-industrial Control Simulation
(Krasting et al. 2016)



Time scales of climate response

Time Scales of Climate Response

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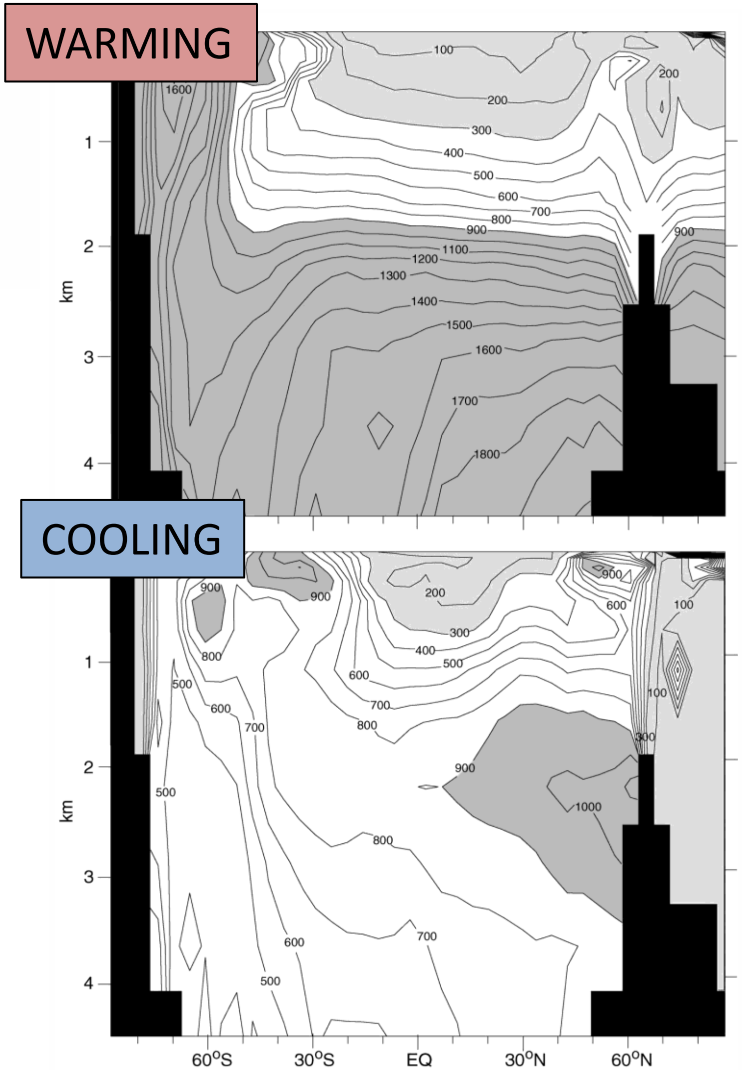
(Manuscript received 9 April 2003, in final form 16 July 2003)

- Ocean cools more rapidly than it warms
- Dynamical changes important, especially in the deep Atlantic
- Ocean mixing is the primary determinant of response time scales

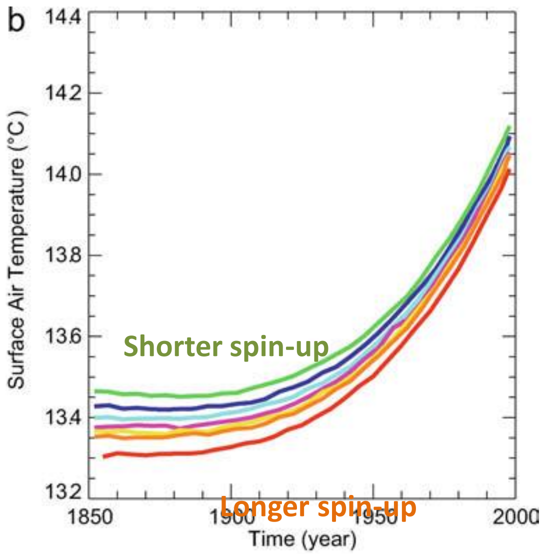
Additional implications for how coupled models are initialized.

Years to reach 70% of equilibrium response

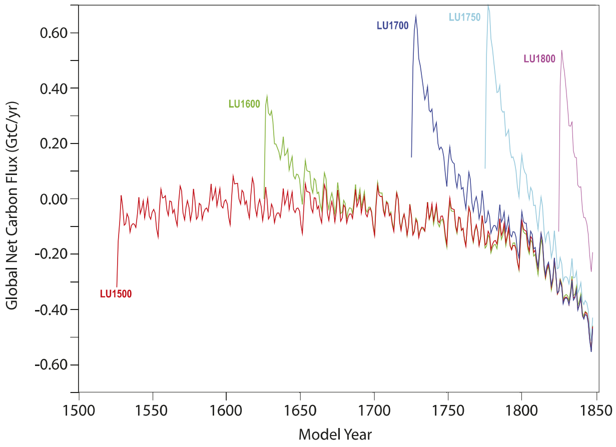


Applications for model initialization

- **"Backspin" method of initializing coupled models**
  Present-day T&S structure in ocean is the integrated result of changes in radiative forcing over the past 1,000 years. Running the radiative forcing backwards and holding constant for several centuries produces a more consistent initial state.



- **Land carbon stocks also have long time scale memory**
  Sentman et al. investigated the length of the spin up for land use transitions have on the carbon fluxes during historical simulations



Future opportunities in understanding CW & LTR

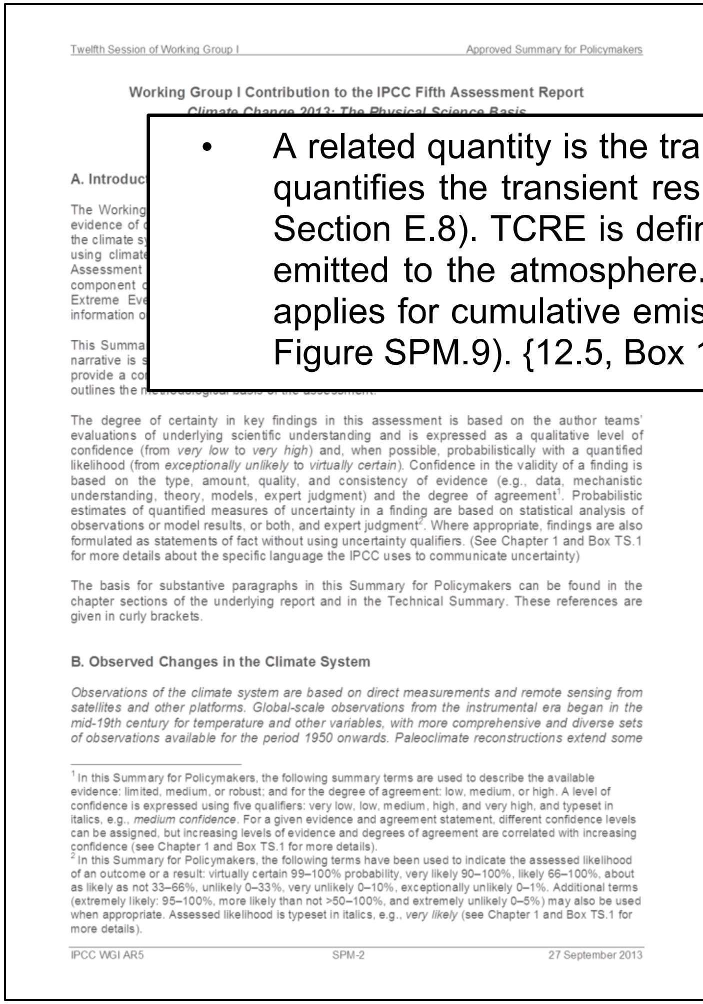
- **Changes in oceanic heat and carbon uptake**
  The interplay between heat and carbon uptake on centennial and millennial time scales are key to the long term climate response to GHG emissions

- **Ocean mixing is determinant of response time scales**
  What impact does different ocean mixing have on heat and carbon uptake?

- **The role of internal climate variability**
  The long time scales of the deep ocean set the oceanic equilibrium time scales on the order of thousands of years. Internal variability is important, especially on decadal to centennial time scales.

IPCC AR5 Summary for Policy Makers

Released September 27, 2013



Twelfth Session of Working Group I — Approved Summary for Policymakers

Working Group I Contribution to the IPCC Fifth Assessment Report

The degree of certainty in key findings in this assessment is based on the author teams' evaluations of underlying scientific understanding and is expressed as a qualitative level of confidence (from *very low* to *very high*) and, when possible, probabilistically with a quantified likelihood (from *exceptionally unlikely* to *virtually certain*). Confidence in the validity of a finding is based on the type, amount, quality, and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement[1]. Probabilistic estimates of quantified measures of uncertainty in a finding are based on statistical analysis of observations or model results, or both, and expert judgment[2]. Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers. (See Chapter 1 and Box TS.1 for more details about the specific language the IPCC uses to communicate uncertainty)

The basis for substantive paragraphs in this Summary for Policymakers can be found in the chapter sections of the underlying report and in the Technical Summary. These references are given in curly brackets.

B. Observed Changes in the Climate System

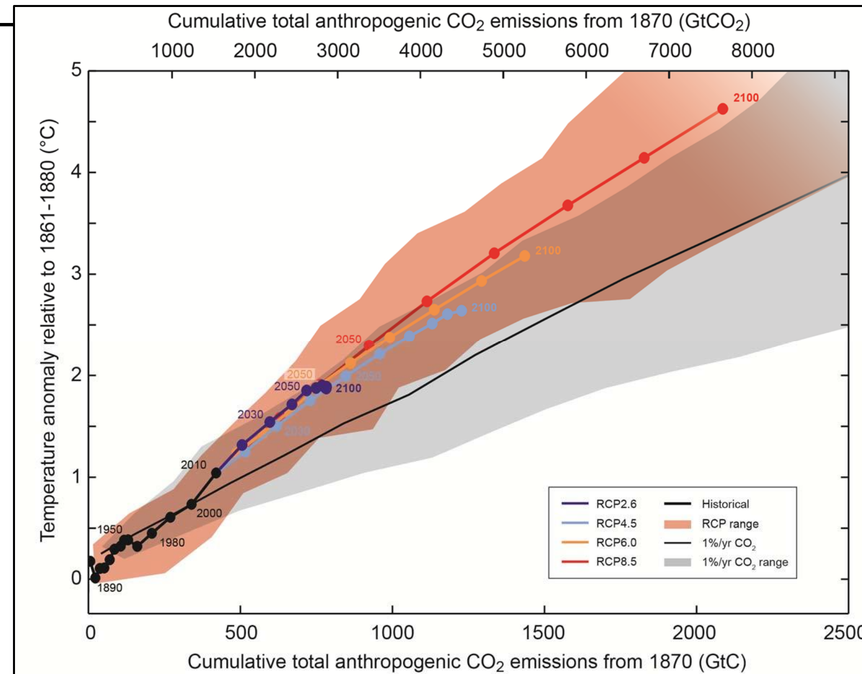
Observations of the climate system are based on direct measurements and remote sensing from satellites and other platforms. Global-scale observations from the instrumental era began in the mid-19th century for temperature and other variables, with more comprehensive and diverse sets of observations available for the period 1950 onwards. Paleoclimate reconstructions extend some

[1] In this Summary for Policymakers, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence (see Chapter 1 and Box TS.1 for more details).

[2] In this Summary for Policymakers, the following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely: 95–100%, more likely than not >50–100%, and extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely* (see Chapter 1 and Box TS.1 for more details).

IPCC WGI AR5 — SPM-2 — 27 September 2013

- A related quantity is the transient climate response to cumulative carbon emissions (TCRE). It quantifies the transient response of the climate system to cumulative carbon emissions (see Section E.8). TCRE is defined as the global mean surface temperature change per 1000 GtC emitted to the atmosphere. TCRE is *likely* in the range of 0.8°C to 2.5°C per 1000 GtC and applies for cumulative emissions up to about 2000 GtC until the time temperatures peak (see Figure SPM.9). {12.5, Box 12.2}



Simplifying Climate-Carbon Cycle Interactions

Vol 459 | 11 June 2009 | doi:10.1038/nature08047

nature

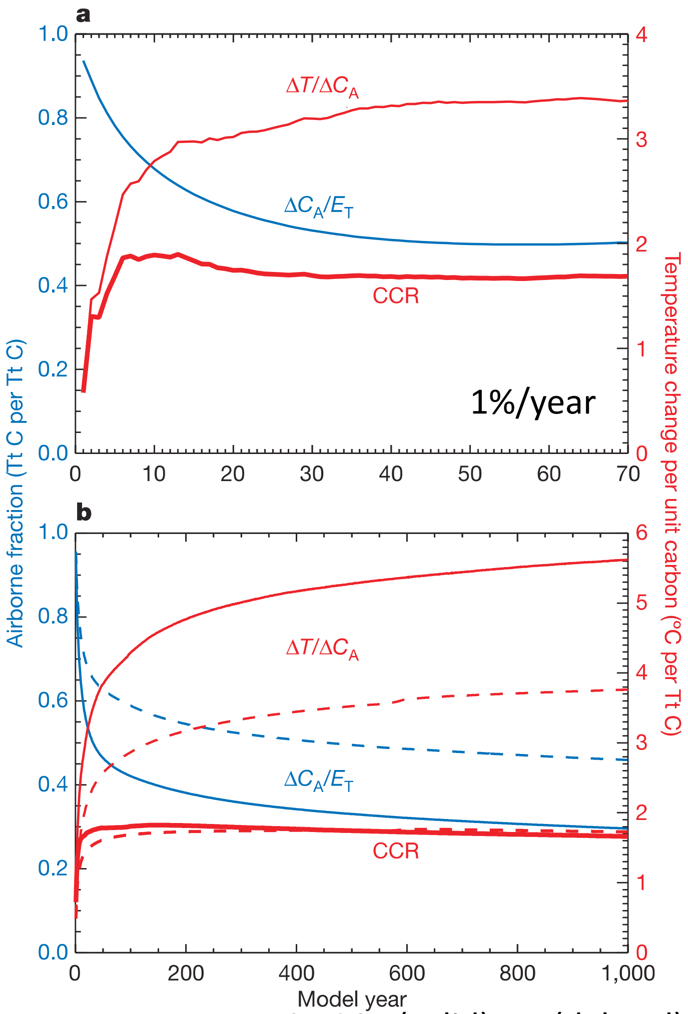
LETTERS

The proportionality of global warming to cumulative carbon emissions

H. Damon Matthews[1], Nathan P. Gillett[2], Peter A. Stott[3] & Kirsten Zickfeld[2]

CO_2 concentration $\xrightarrow{\text{Climate sensitivity}}$ Climate change

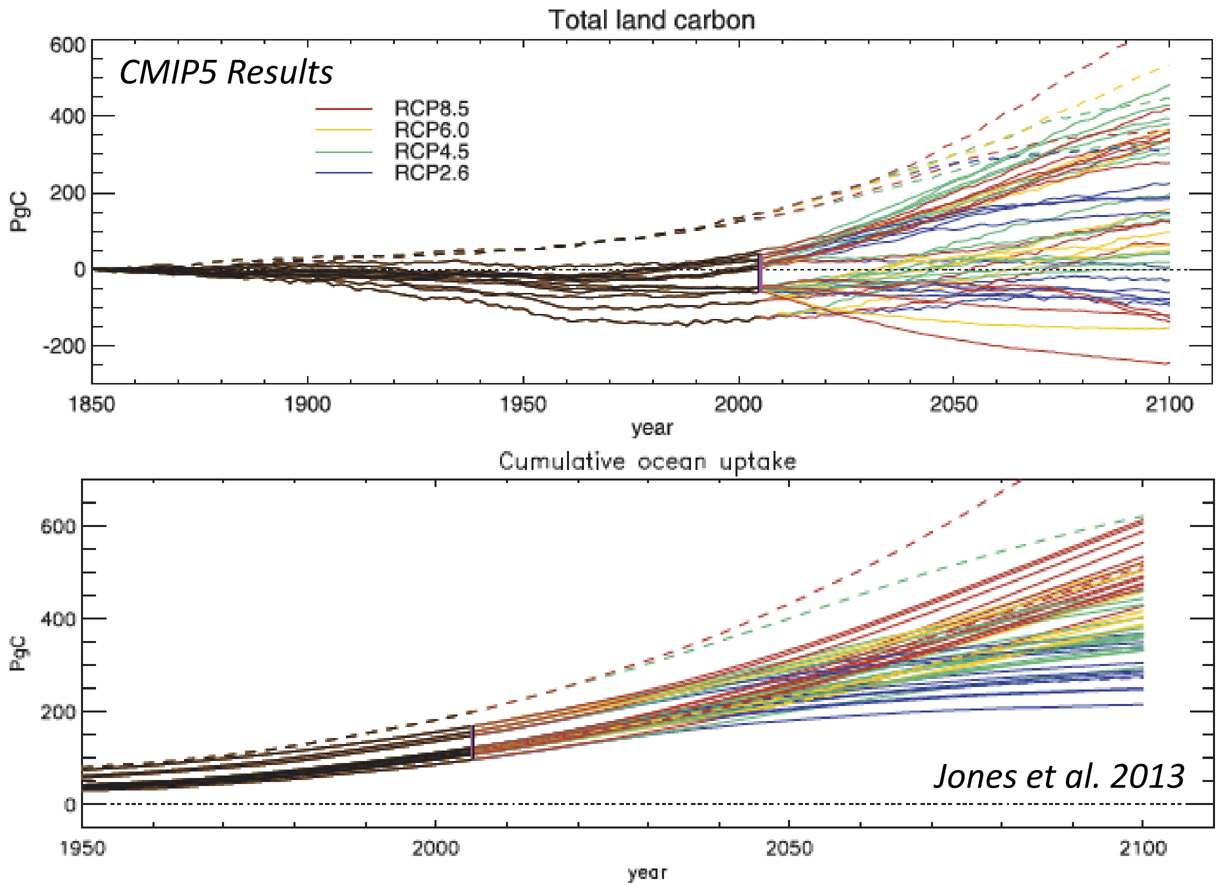
Properties of TCRE



Instantaneous 2x CO2 (solid), 4x (dahsed)

- Valid for emissions below 2000 GtC and on time scales of 20 to 1000 years (Matthews et al.)
- Temperature and carbon emissions linearly related since similar oceanic process govern both heat and carbon uptake (Matthews et al.)

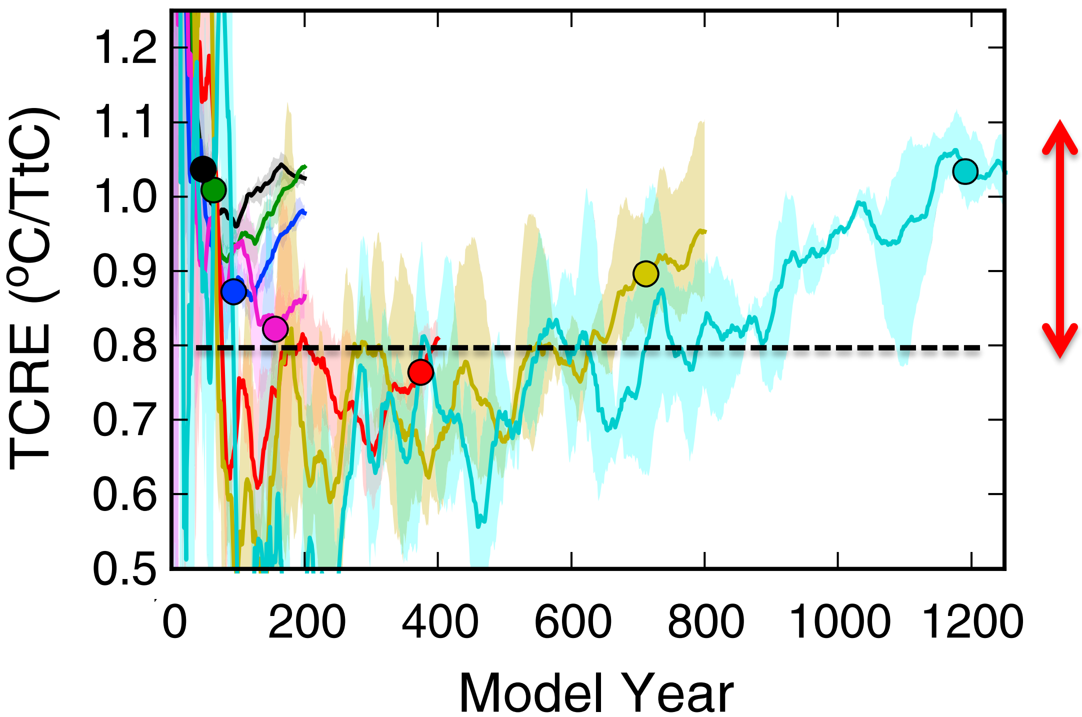
Uncertainty in Future Carbon Uptake



Land a net carbon source by year 2100 in some models

Feedbacks between climate system and carbon cycle are uncertain.

Variability and Uncertainty in TCRE vs. Time



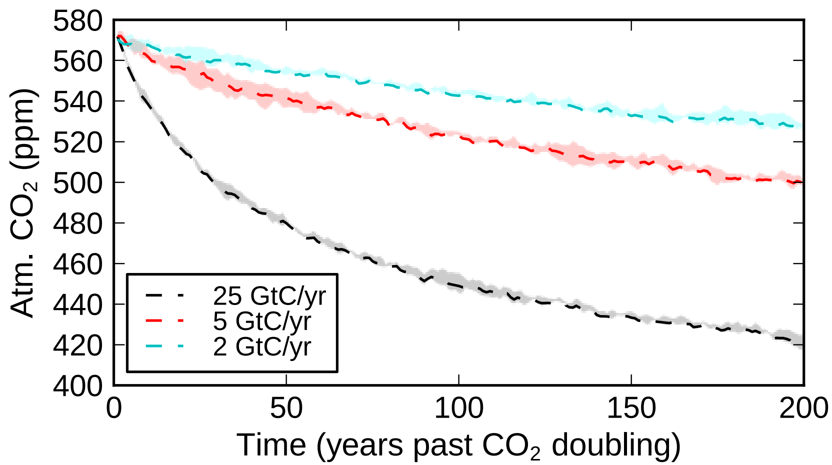
IPCC Range: 0.8 to 2.5 ºC/TtC

GFDL-ESM2G TCRE ranges from 0.77 to 1.04 ºC/TtC across the 5 emission rate scenarios

- Variability in TCRE makes the 5 scenarios indistinguishable over the first 100 years
- As the signal-to-noise ratio becomes more favorable with time, separation of the scenarios is evident

Response to Zero-emissions After CO_2 Doubling

After reaching 572 ppm, no additional emissions were applied to the model



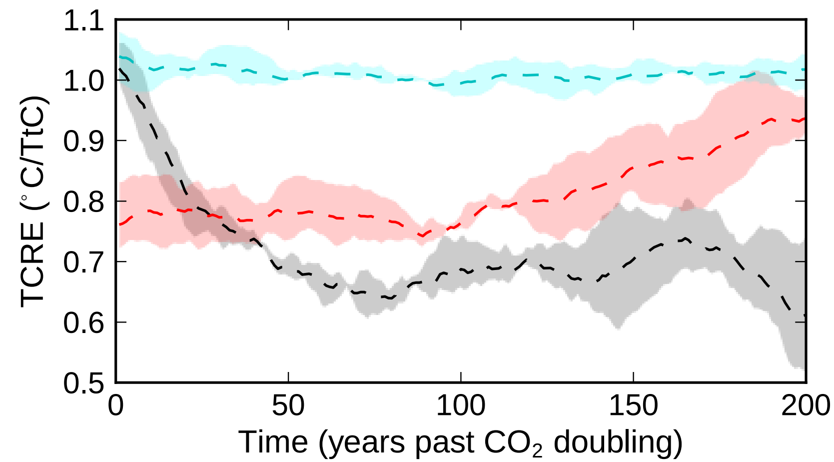


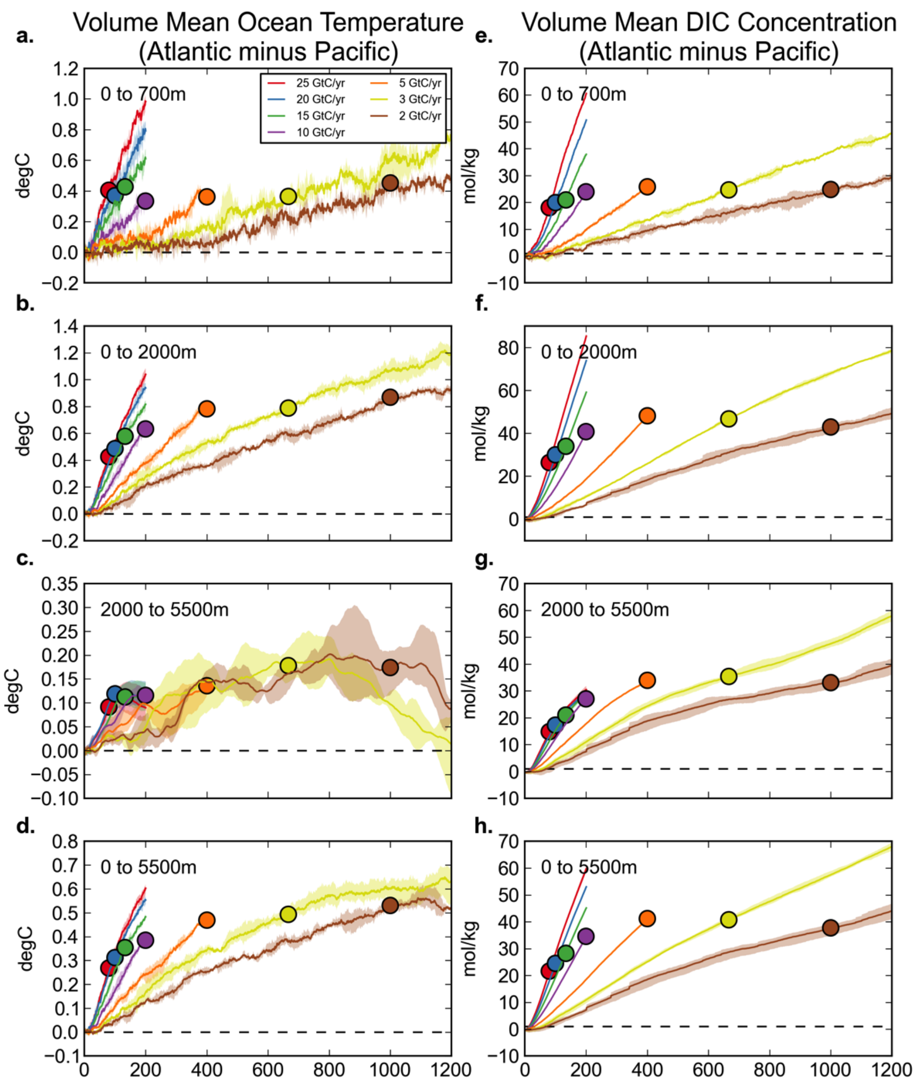
Table 2. Climate and Carbon Cycle Response 100 and 200 Years After the Imposition of Zero Emissions at the Time of CO_2 Doubling[a]

	Land Uptake		Ocean Uptake		ΔT		TCRE	
	+100 years	+200 years	+100 years	+200 years	+100 years	+200 years	+100 years	+200 years
2-to-0 GtC/yr	542 (7.6)	511 (9.6)	1242 (19.6)	1310 (20.2)	2.37 (0.032)	2.41 (0.041)	0.99 (0.003)	1.01 (0.025)
5-to-0 GtC/yr	567 (10.6)	534 (11.7)	741 (6.5)	829 (6.9)	1.40 (0.046)	1.74 (0.095)	0.75 (0.018)	0.94 (0.057)
25-to-0 GtC/yr	444 (10.8)	423 (9.3)	369 (1.3)	451 (1.8)	0.8 (0.047)	0.78 (0.103)	0.66 (0.039)	0.65 (0.086)

[a]Land and ocean carbon uptake (GtC) are cumulative from year 1 of the experiments. ΔT (°C) computed as a 20 year average (years 81–100 and 181–200). Values represent a mean across ensemble members and the 1σ standard deviation is given in the parenthesis.

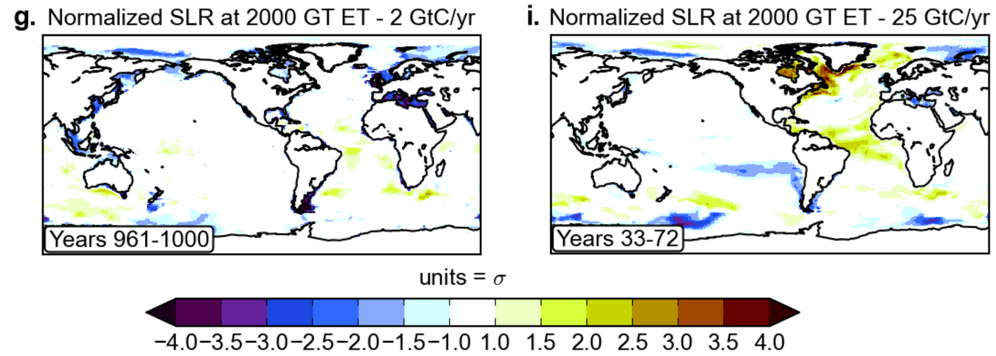
“Recalcitrant” warming (Held et al. 2010) in the 5 GtC/year scenario – TCRE increases

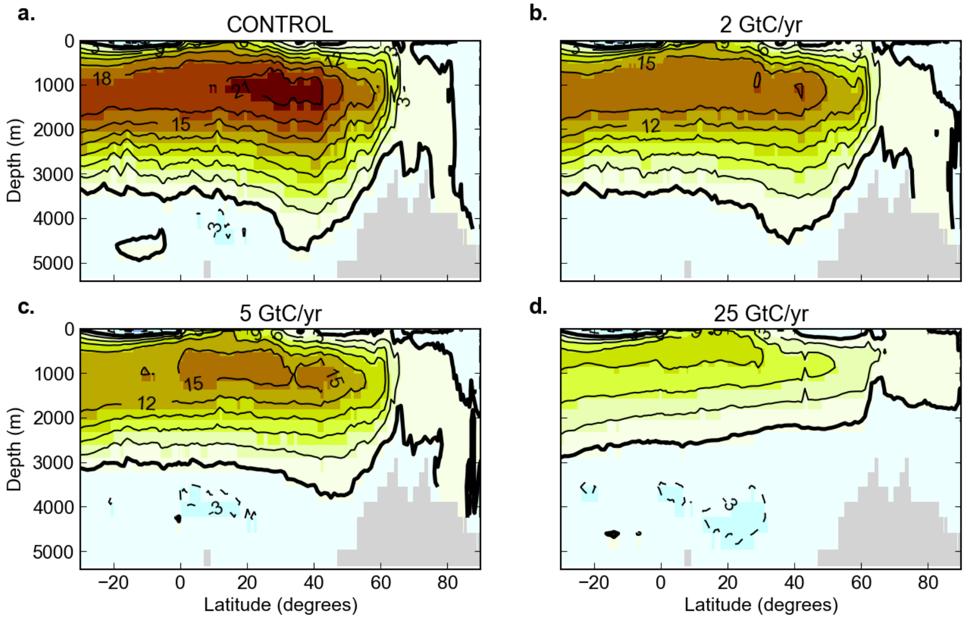
Oceanic Heat vs. Carbon Uptake



- On short time scales, and above 2000 m, Atlantic minus Pacific heat and carbon uptake are similar
- On time scales of the deep Pacific (>600 years), heat uptake “catches up” to the Atlantic, while carbon uptake does not
- Basin-scale heat uptake differences translate into basin differences in sea level rise.

Oceanic Heat vs. Carbon Uptake





Krasting et al. 2016

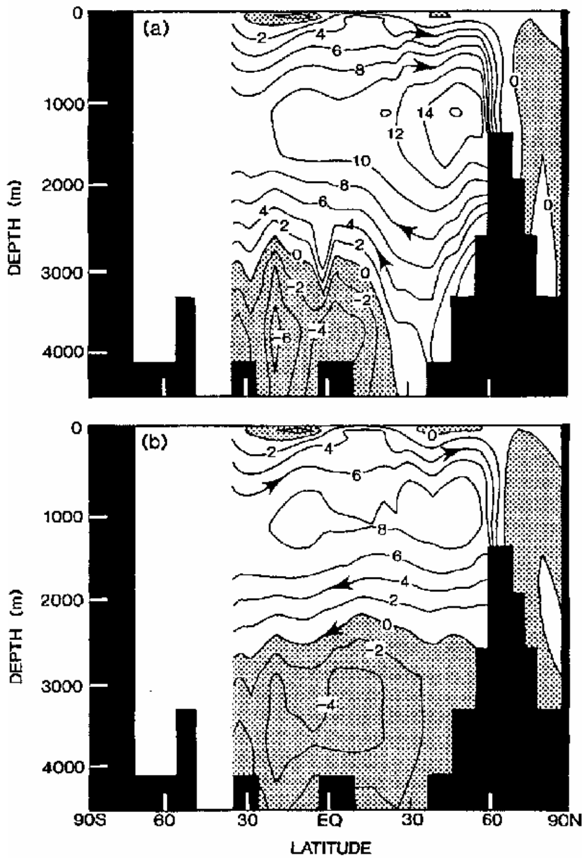
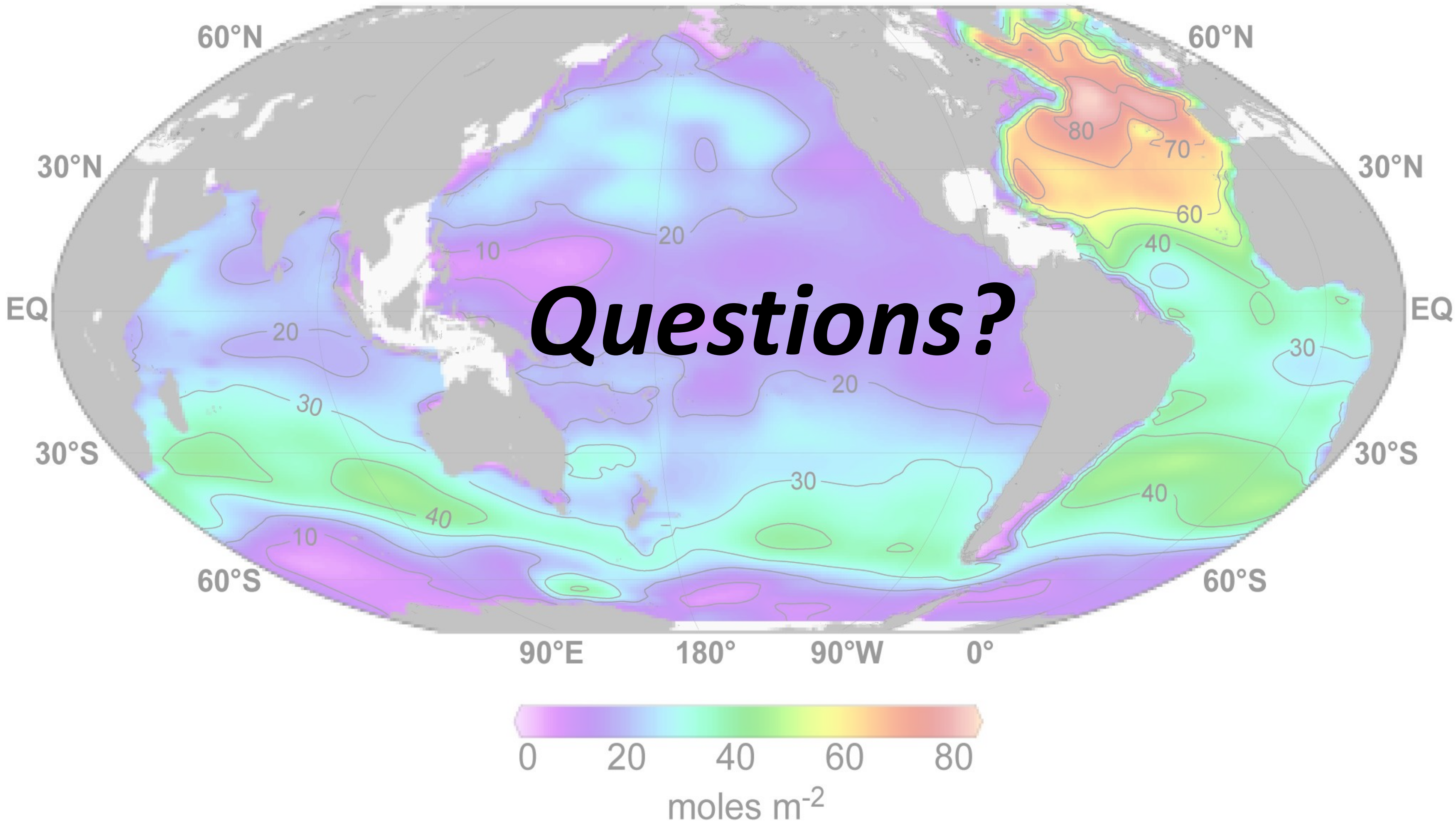


FIG. 9. Latitude–depth distribution of the meridional streamfunction in the Atlantic Ocean (Sv). (a) The 4% integration and (b) the 0.25% integration. The contour interval is 2 Sv. Negative values are shaded. See Table 1 for the periods used to compute the time averages.

Stouffer and Manabe, 1998

Summary

- GFDL, through Ron's pioneering work, has been a world leader in understanding the long-term response to anthropogenic climate forcing
  - Important for understanding committed warming
  - Implications for model development & initialization
- Heat and carbon uptake are primary drivers of the long-term response
  - ESMs allow coupled exploration of heat and carbon uptake
  - Exploring the limits of TCRE
  - Rate of emissions/warming linked to the ocean dynamical response
- Exploring other long time scale processes is important
  - Natural variability of vegetation dynamics & soil carbon
  - Fate of the natural carbon sinks


Questions?
60°N
30°N
EQ
30°S
60°S
90°E
180°
90°W
0°
80
70
60
40
30
20
10
0
20
40
60
80
moles m-2

Simplifying Uncertainties in Climate-Carbon Cycle Interactions

Vol 458 | 30 April 2009 | doi:10.1038/nature08019 nature

LETTERS

Warming caused by cumulative carbon emissions towards the trillionth tonne

Myles R. Allen[1], David J. Frame[1,2], Chris Huntingford[3], Chris D. Jones[4], Jason A. Lowe[5], Malte Meinshausen[6] & Nicolai Meinshausen[7]

Allen et al. (2009) demonstrate peak climate warming proportional to cumulative carbon emissions.

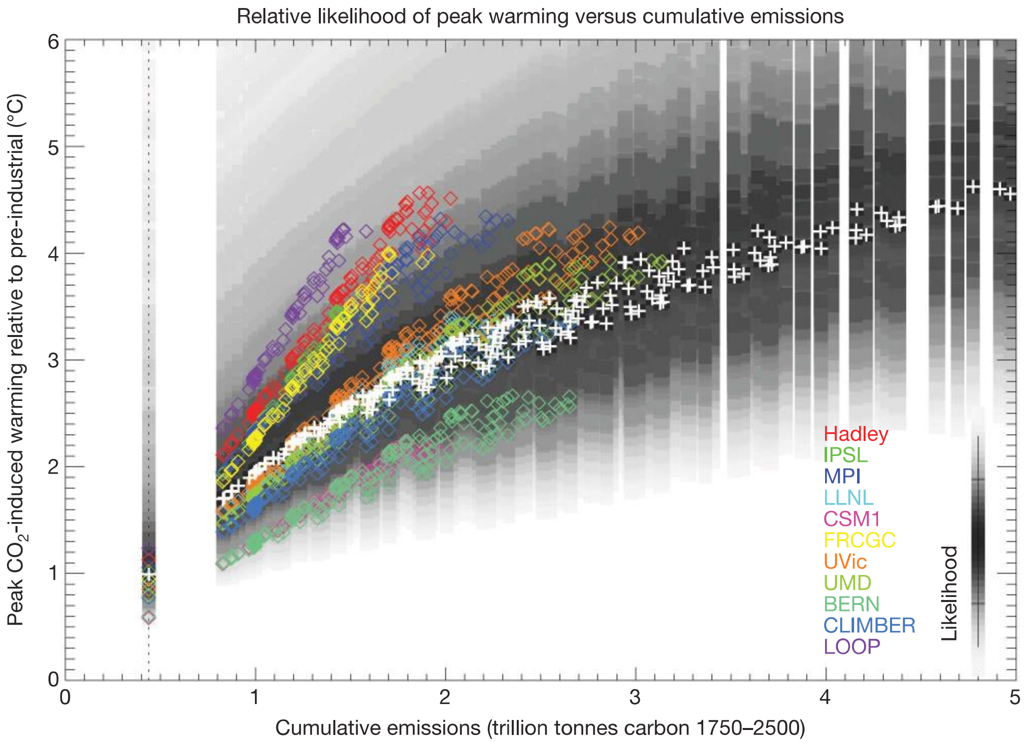
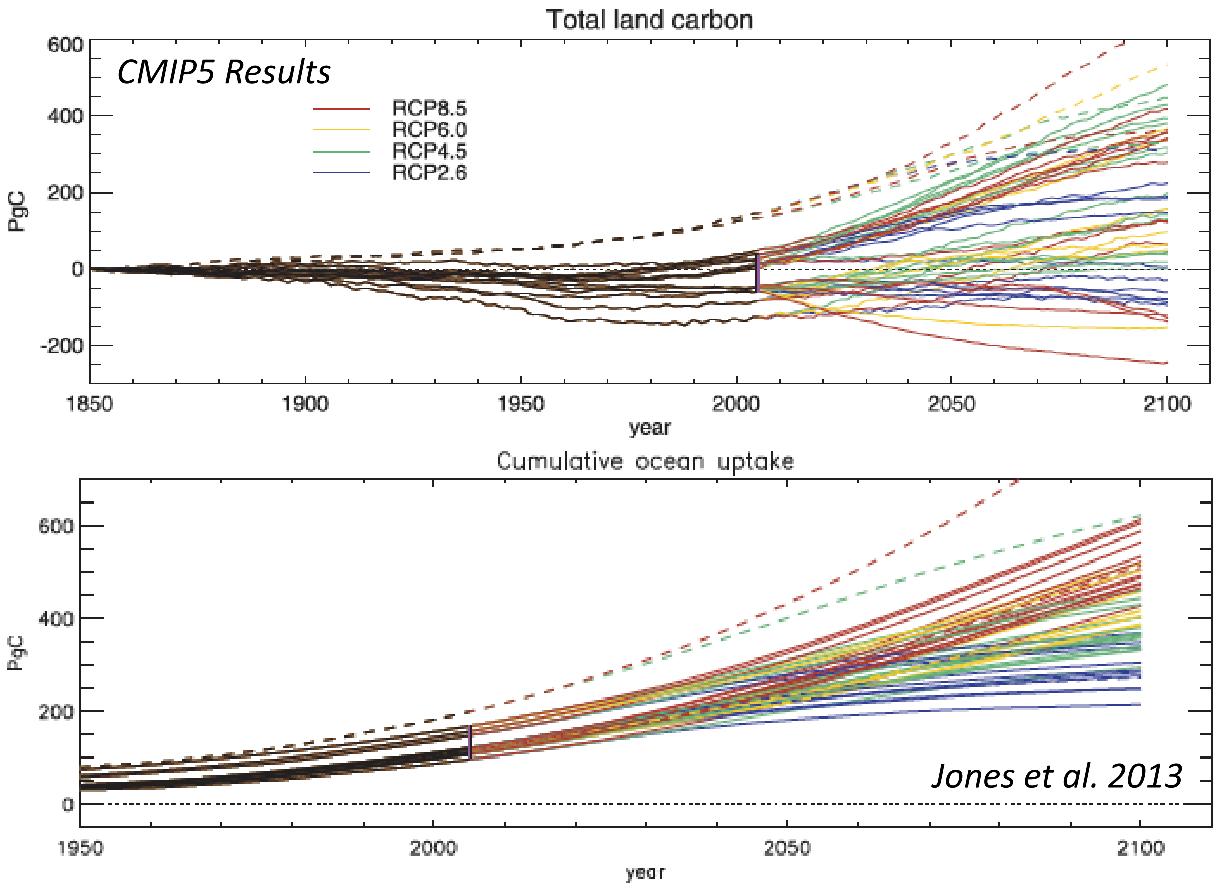


Figure 2 | Peak CO_2-induced warming as a function of total cumulative emissions 1750–2500 for 250 idealized emission scenarios. (A subset is plotted as black lines in Fig. 1a.) White crosses correspond to best-fit values of simple climate model parameters, with each cross corresponding to a single scenario. Grey shading shows relative likelihood of other parameter combinations, plotted in order of increasing likelihood, showing the uncertainty in peak warming arising from parameter uncertainty in the simple model. Coloured diamonds show responses of the HadSCCCM1 model with parameters fitted to ESMs in the C^4MIP experiment, with colours indicating the corresponding ESM. Diamonds are plotted only where temperatures remain within 0.5 °C of the range of the tuning data set (the SRES A2 scenario) to ensure a valid emulation. Bar and symbols at 0.44 Tt C show peak warming assuming zero emissions after 2000. Likelihood scale bar as in Fig. 1b.

Uncertainty in Future Carbon Uptake

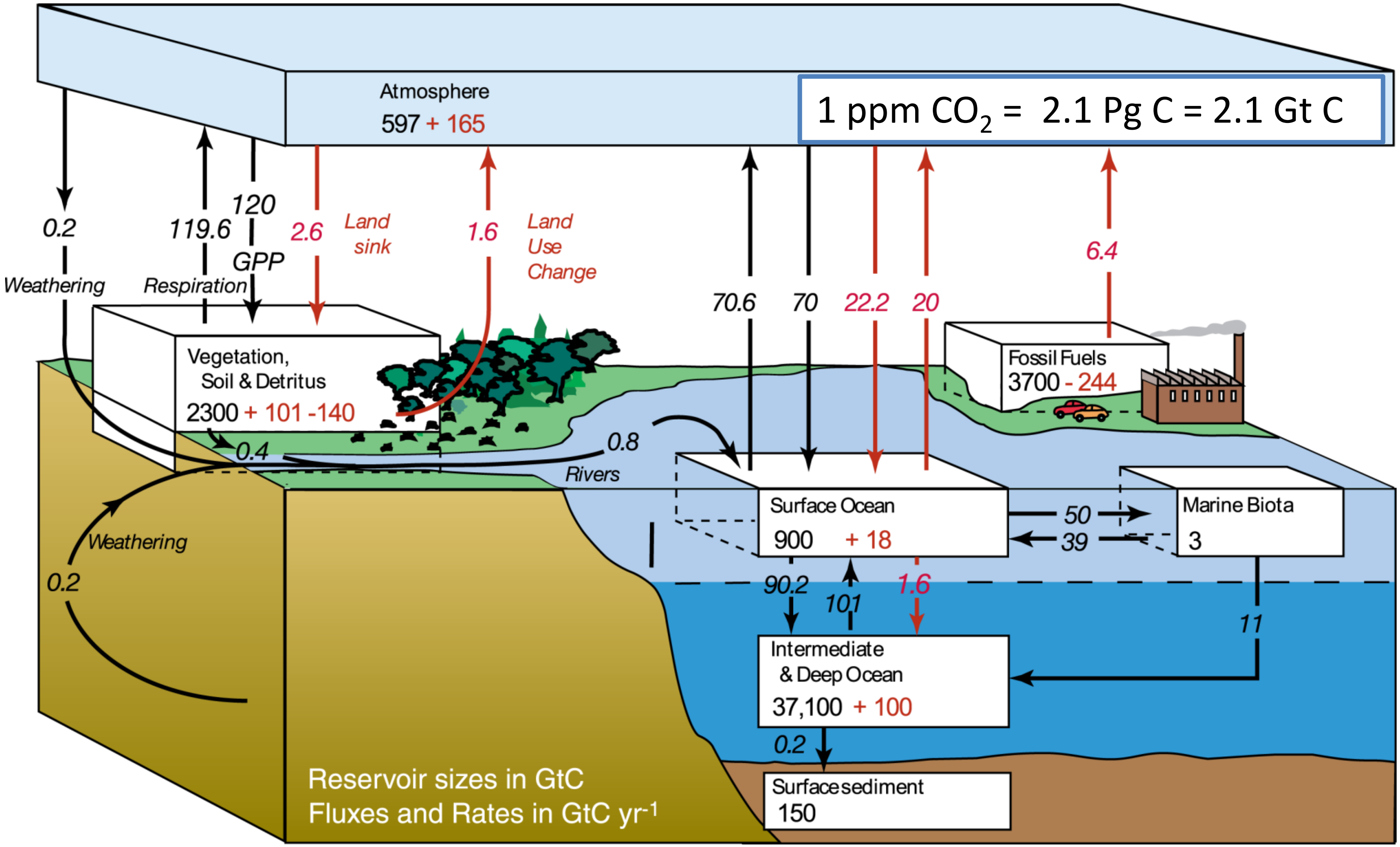


Land a net carbon source by year 2100 in some models

Feedbacks between climate system and carbon cycle are uncertain.

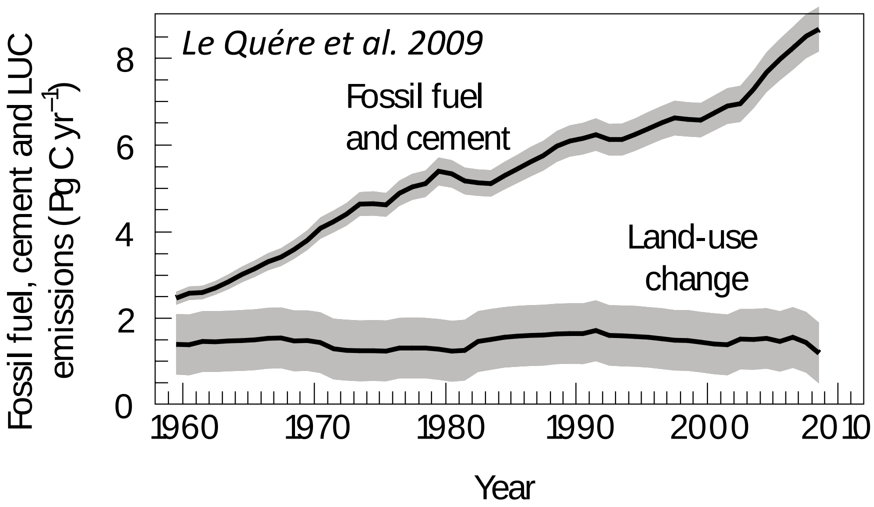
Human Perturbation to the Carbon Cycle

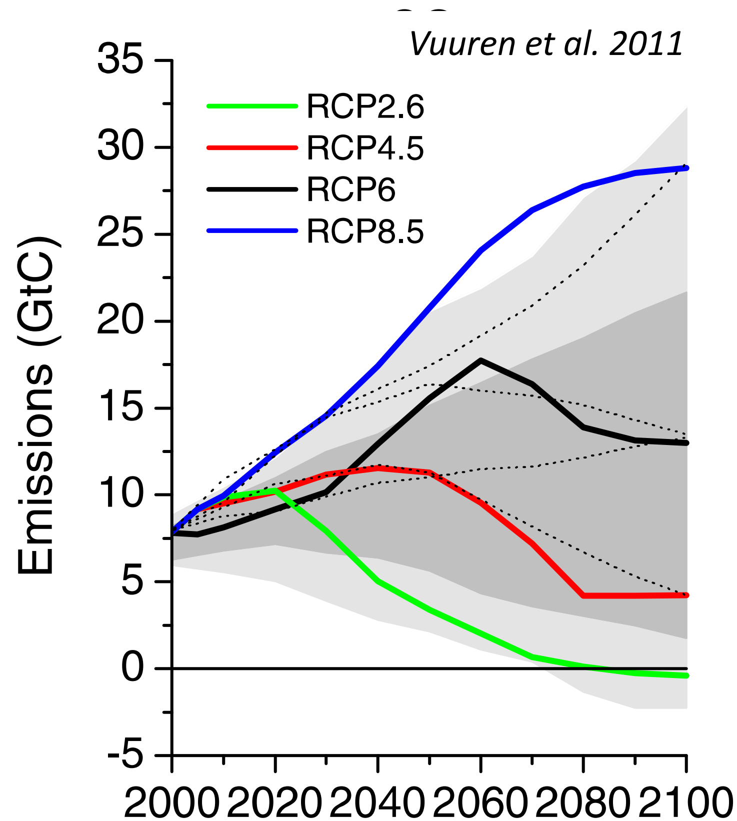
$1\ ppm\ CO_2 = 2.1\ Pg\ C = 2.1\ Gt\ C$



IPCC AR4WG1 Figure 7.3. The global carbon cycle for the 1990s, showing the main annual fluxes in GtC yr–1: pre-industrial 'natural' fluxes in black and 'anthropogenic' fluxes in red (modified from Sarmiento and Gruber, 2006, with changes in pool sizes from Sabine et al., 2004)

Past and Future Carbon Emissions





- Rate of historical carbon emissions is increasing
- Emissions may increase 4-fold by year 2100 … or decrease

Land CO_2 Fertilization

PNAS

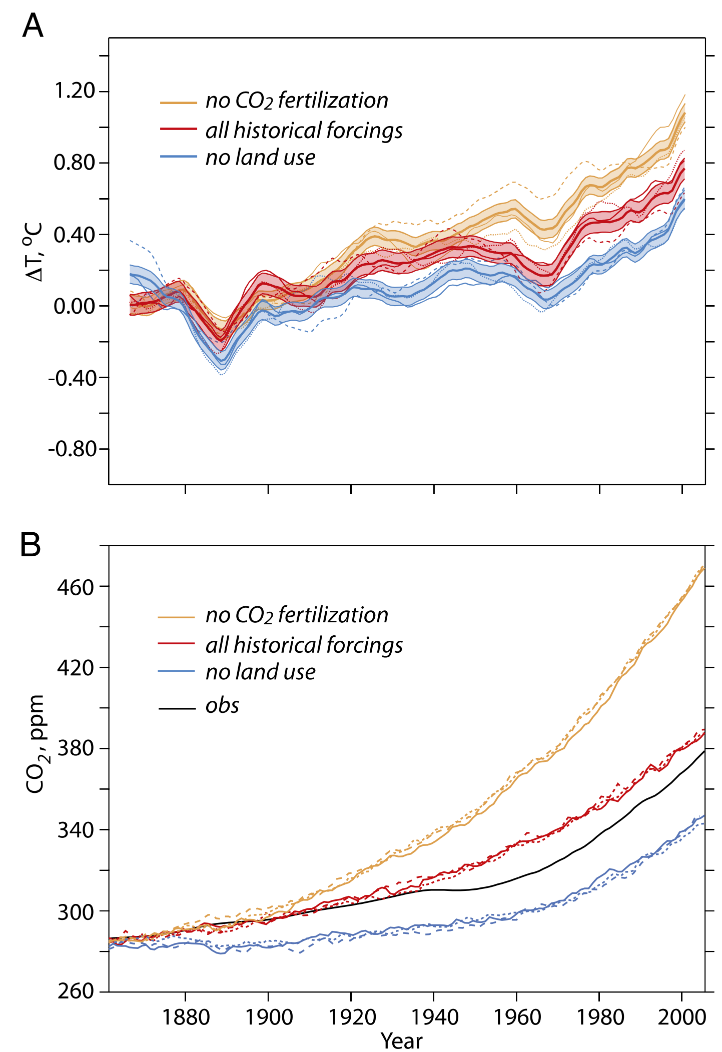
Historical warming reduced due to enhanced land carbon uptake

Elena Shevliakova[a], Ronald J. Stouffer[b], Sergey Malyshev[a], John P. Krasting[b], George C. Hurtt[c], and Stephen W. Pacala[a,1]

[a]Department of Ecology and Evolutionary Biology, Princeton University, Princeton, NJ 08544; [b]Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton, NJ 08540; and [c]Department of Geographical Sciences, University of Maryland, College Park, MD 20742

Contributed by Stephen W. Pacala, August 13, 2013 (sent for review December 3, 2012)

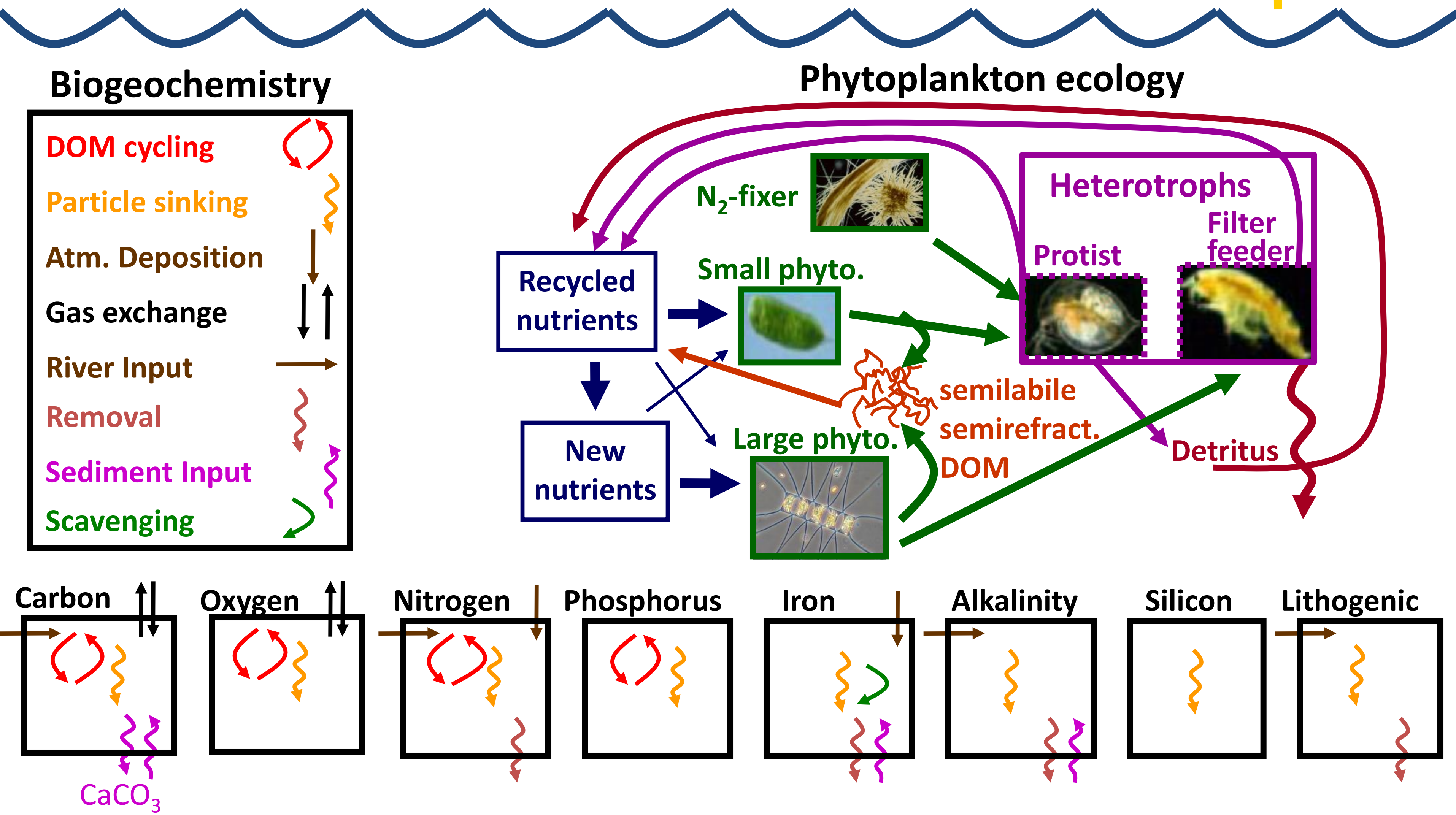
- Land use a large source of carbon during the historical period
- Model representation of land use, vegetation and CO_2 fertilization is important
- Enhanced land uptake limited historical CO_2 growth by ~85 ppm and warming by ~0.3 ºC



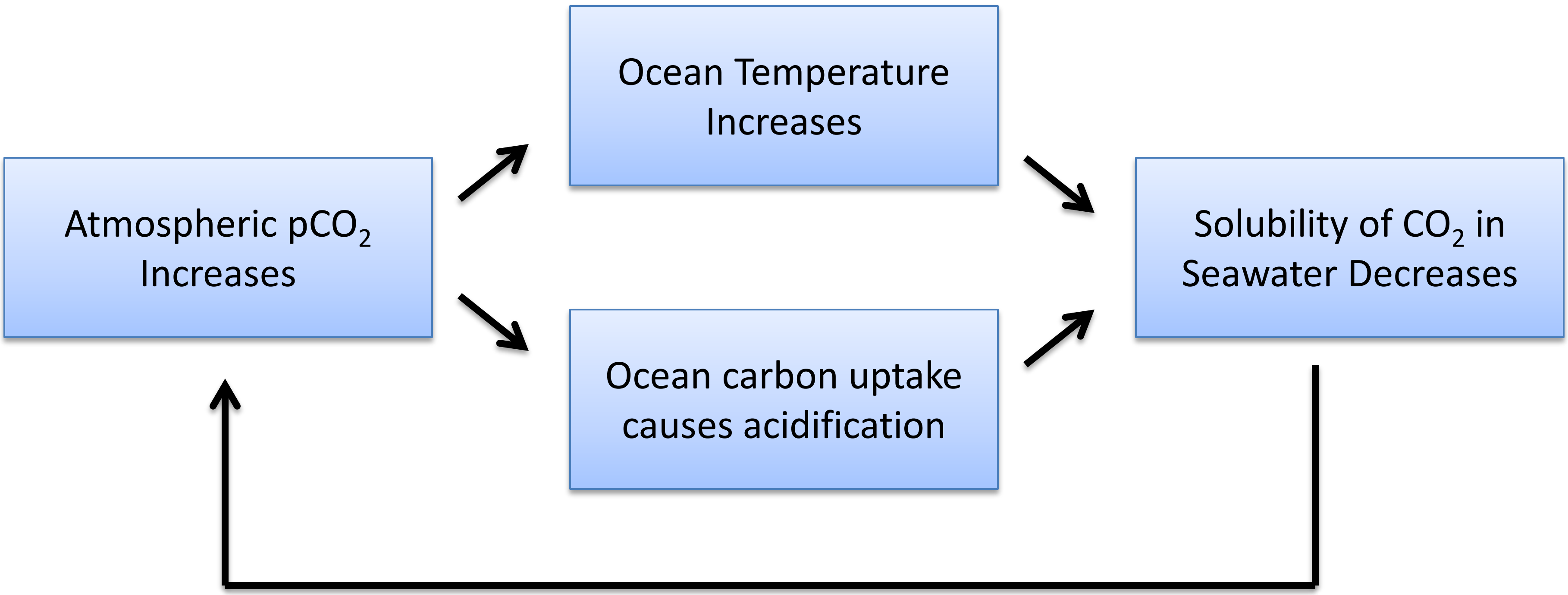
Tracers of Phytoplankton with Allometric Zooplankton (TOPAZ)

Implicit grazing dynamics
Flexible N:P:Si:Fe:Chl
Aragonite and Calcite

30 Tracers

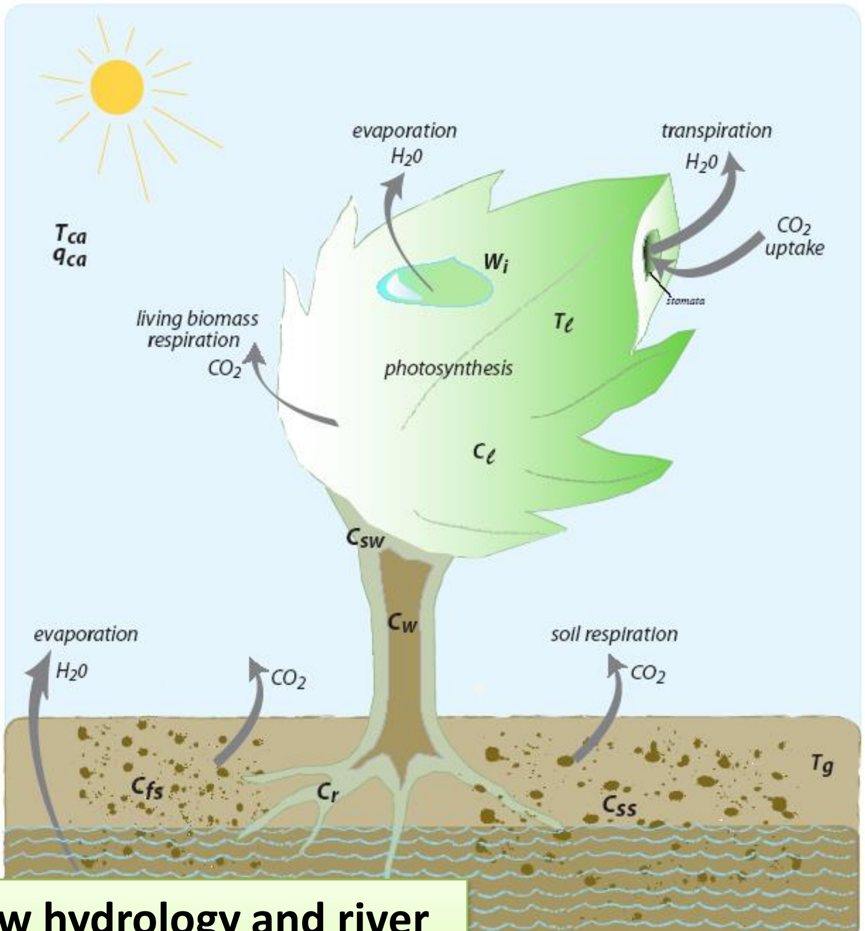


Climate-Carbon Feedback Example



- Many other feedbacks to consider on land and in the ocean

GFDL's ESMs Incorporate a New Land Model - LM3

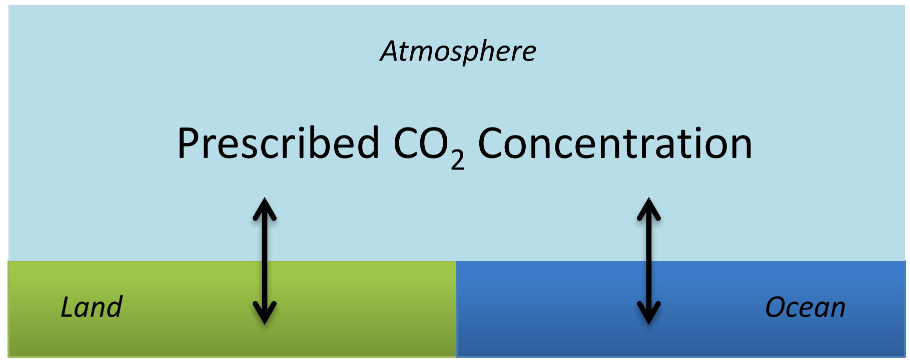


New hydrology and river routing scheme

- **<u>5 vegetation types</u>: warm grasses, cold grasses, tropical, deciduous, coniferous**
- **<u>5 vegetation C pools</u>: leaves, sapwood, wood, fine roots, virtual leaves**
- **<u>2 soil C pools</u>: fast, *slow***
- **<u>4 land-use types</u>: Primary, Crop, Pasture, Secondary Forest**
- **Up to 15 tiles of different forest ages per grid-cell**
- **Natural mortality and annual fire**

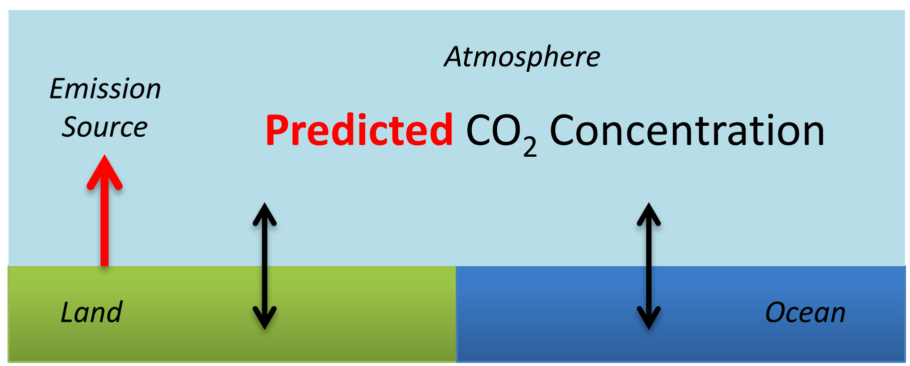
Experimental Design

Classical Experimental Design



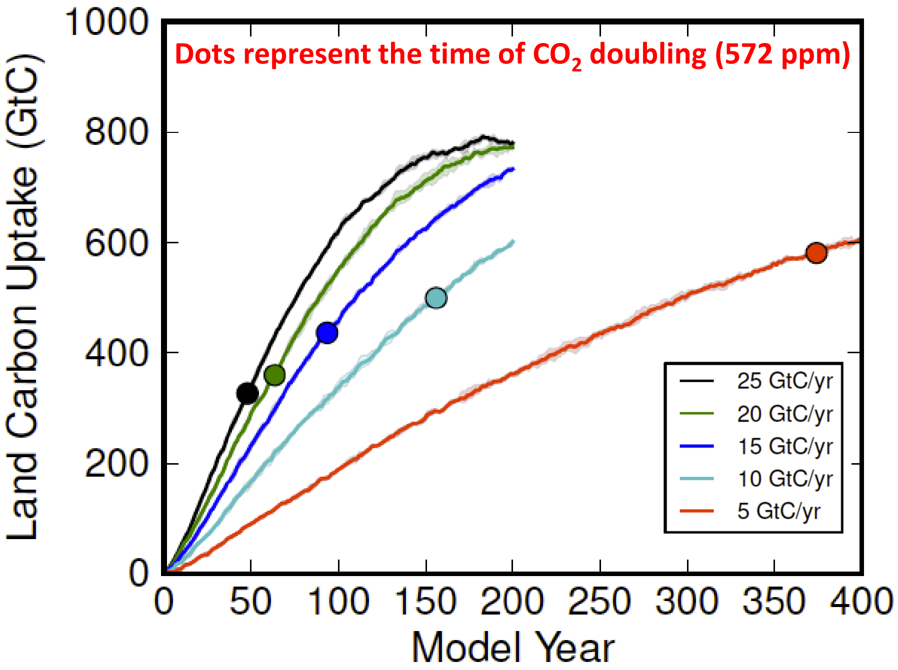
Carbon emissions diagnosed from fluxes

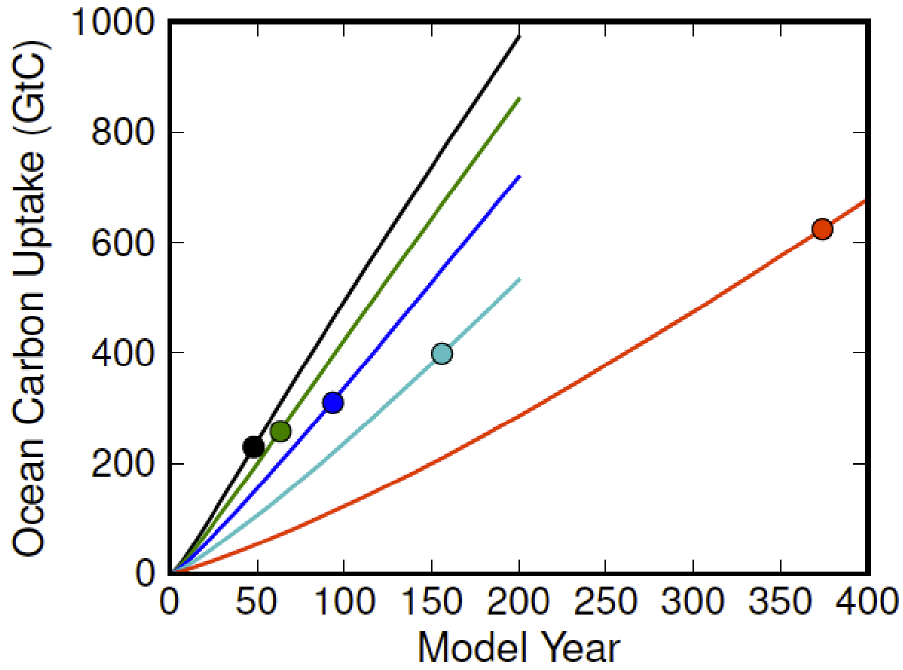
ESM Experimental Design



Carbon emissions given to the model

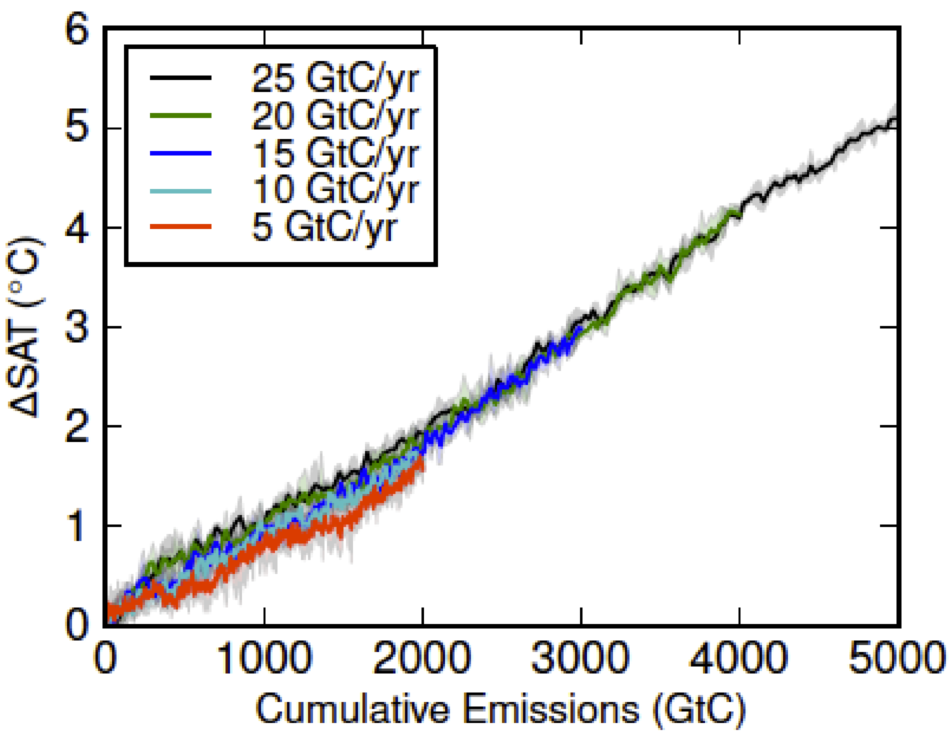
Land/Ocean Carbon Storage





- Land and ocean carbon uptake is non-linear with respect to time and CO_2 concentration
- Slower emission rates allow the land and ocean to take up more carbon at the time of CO_2 doubling

Temperature vs. Cumulative Emissions



To a first order, temperature and cumulative emissions are linearly related.

TCRE is robust in GFDL-ESM2G when forced with emissions.

Clear separation among the 5 different emission rates. Lower emission rates produce less warming per emitted carbon as compared to the higher emission rates.

Scenarios compared with 1%/year Exps.

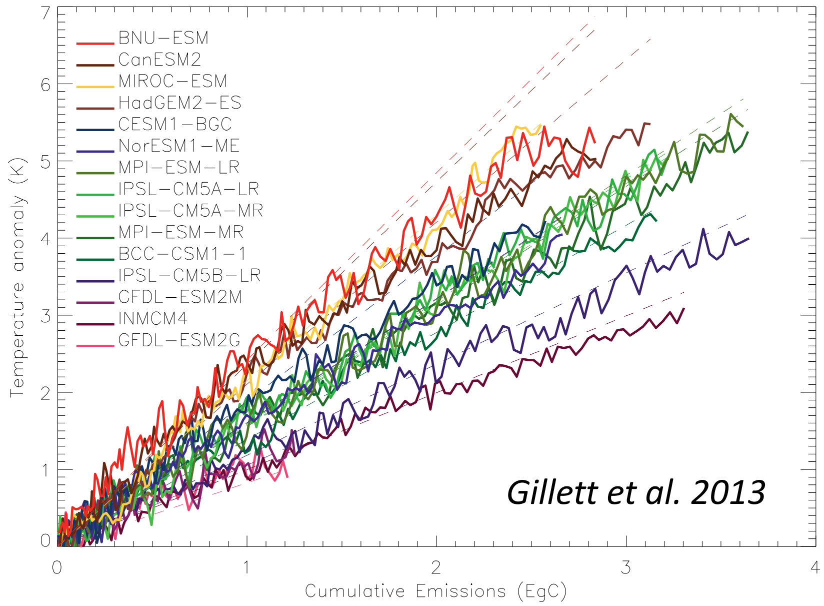
- The 1%/year prescribed concentration scenarios compare with the 20 and 25 PgC/yr scenarios. (Higher than present-day emissions and at the upper range of future scenarios)
- Slower emission rates → ocean takes up more carbon than land
- Higher emission rates → land takes up more carbon than ocean.

	Year of 2xCO_2	E_T	Land Uptake	Ocean Uptake	τ	ΔT	TCRE
5 Pg/yr	370 / 376 / 371	1850 / 1880 / 1855	579 (8.0)	620 (6.1)	384 (61.8)	1.43 (0.118)	0.77 (0.066)
10 Pg/yr	154 / 154 / 154	1540 / 1540 / 1540	491 (5.9)	392 (1.7)	213 (5.1)	1.27 (0.029)	0.82 (0.019)
15 Pg/yr	92 / 94 / 93	1380 / 1410 / 1395	436 (10.0)	309 (3.0)	151 (3.3)	1.23 (0.012)	0.88 (0.015)
20 Pg/yr	63 / 64 / 63	1260 / 1280 / 1260	362 (10.8)	259 (2.7)	115 (3.9)	1.27 (0.102)	1.0 (0.089)
25 Pg/yr	48 / 48 / 48	1200 / 1200 / 1200	326 (2.3)	229 (0.5)	96 (2.8)	1.25 (0.002)	1.04 (0.001)
1%/yr to 2x	70	1184	327	239	119	1.14	0.96
1%/yr to 4x	70	1194	339	238	103	1.26	1.05

Scenario Dependence in Context

•There is ~20% difference in TCRE between the highest and lowest emissions scenario for GFDL-ESM2G

•This represents 1/3 of the spread across the C^{4}MIP models and ~1/8 of the spread across CMIP5 models



•Scenario dependence matters when considering emissions that are either substantially higher or lower than present day emissions

•Largest source of uncertainty in TCRE from model differences.

•GFDL-ESM2G TCR (1.3 K) is low compared to CMIP3 mean (1.8 K)

Four non-linear aspects of TCRE

1. Radiative forcing in the atmosphere

$$RF \approx 5.35 \ln(\Delta CO_2)$$ *Myhre et al. 1995*

2. Efficacy of oceanic heat uptake
3. Land carbon uptake saturates at ~800 GtC
4. Ocean carbon uptake accelerates slightly with time

Application of TCRE to Climate Policy

- TCRE, in its elegance and simplicity, has gained popularity in climate and policy communities.

- TCRE used in discussions of the 2009 Copenhagen Accord (limiting global temp. rise to 2ºC)

- TCRE not valid in all emission scenarios (i.e. extremely high or low emission rates, zero-emissions)

- Time scales of emissions are important. How do they correspond public policy time scales?

Summary

- Temperature and cumulative emissions are proportional in GFDL-ESM2G when forced with varying emission rates

- Emission pathways matter, but larger challenge is constraining model physics.

- Lower emission rates produce less warming per unit of emitted carbon.

- Idealized linear emission scenarios a potential alternative to classical 1%/year experiments

- Mechanisms of TCRE are more complex than oceanic heat and carbon uptake alone

5^{th} Coupled Model Intercomparison Project (CMIP5)

Previous Special Report on Emission Scenarios (SRES): 6 Families and 40 Scenarios

Present Representative Concentration Pathways (RCP): Reduces to 4 main scenarios

	Radiative Forcing	Concentration	Pathway	RCP Model	Reference
RCP8.5	>8.5 W m^{-2} in 2100	>1370 CO_2-eq in 2100	Rising	MESSAGE	Rao and Riahi (2006), Riahi et al. (2007)
RCP6.0	~6 W m^{-2} in 2100	~850 CO_2-eq (stabilization after 2100)	Stabilization without overshoot	AIM	Fujino et al. (2006), Hijioka et al. (2008)
RCP4.5	~4.5 W m^{-2} in 2100	~650 CO_2-eq (stabilization after 2100)	Stabilization without overshoot	MiniCAM	Smith and Wigley (2006), Clarke et al. (2007)
RCP2.6	Peak at ~3 W m^{-2} before 2100 and then decline	~490 CO_2-eq before 2100 and then decline	Peak and decline	IMAGE	van Vuuren et al. (2006, 2007)

Emissions thus far outstrip projections

Peters et al., 2012: The challenge to keep global warming below 2°C. *Nat. Clim. Change*, **3**, 4-6.

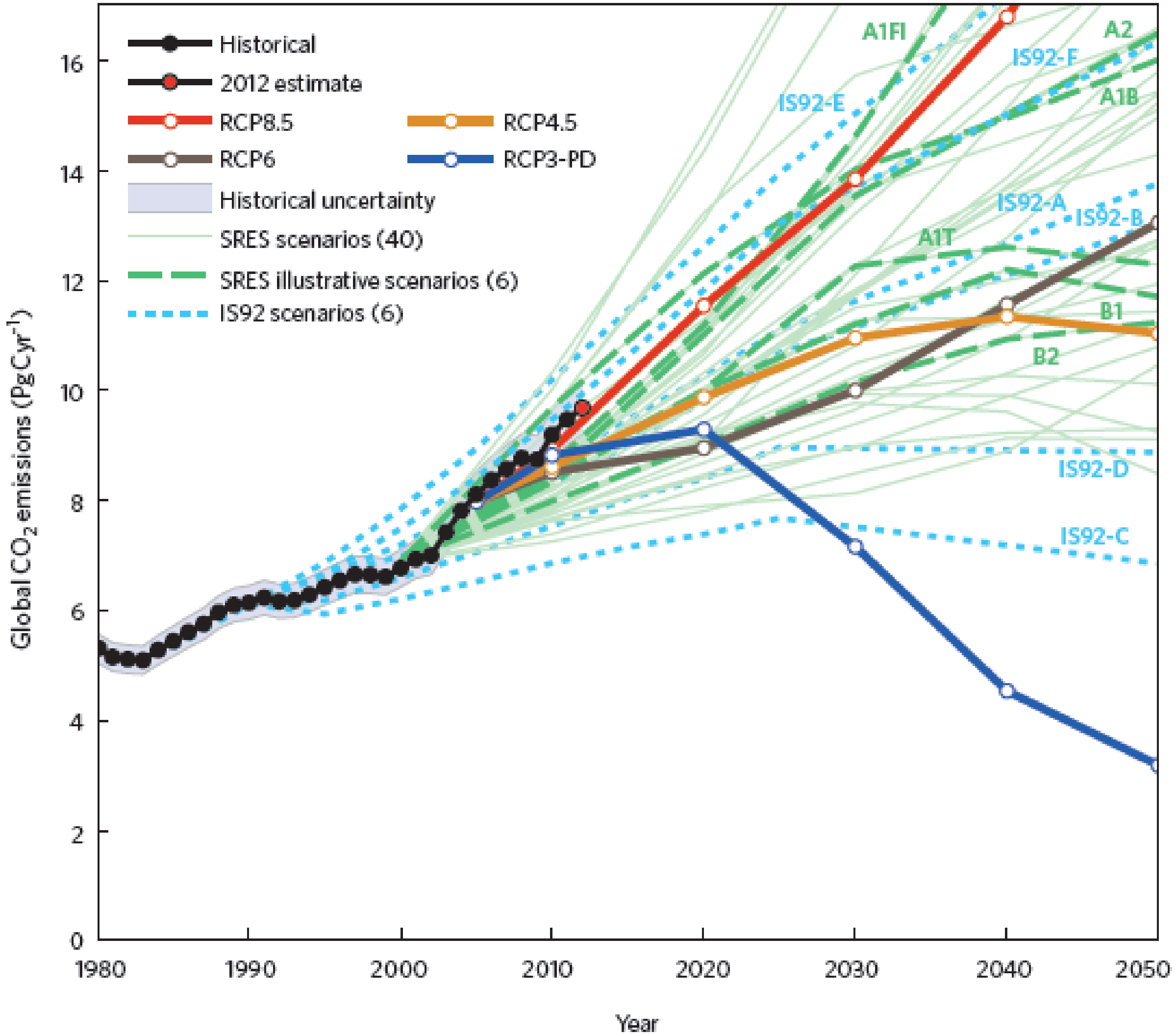


Figure 1 | Estimated CO_2 emissions over the past three decades compared with the IS92, SRES and the RCPs. The SA90 data are not shown, but the most relevant (SA90-A) is similar to IS92-A and IS92-F. The uncertainty in historical emissions is ±5% (one standard deviation). Scenario data is generally reported at decadal intervals and we use linear interpolation for intermediate years.